Faculty Working Papers

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EXIST IN WATER UTILITY?

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Abstract

Relationships between the capacity of a water treatment plant and the construction costs of major components of the plant were analyzed using cost data available in original contractual documents. The result of the analysis showed diseconomies of scale in capital cost of each of the components. Although less conclusive, the total cost of water treatment also indicated diseconomies of scale for a plant in the upper two thirds of the intermediate capacity range.

Introduction

Economies of scale are considered one of the main reasons for constructing a larger plant instead of a set of smaller ones. Past studies have proved that such economies indeed exist in various types of productive facilities. But this is not necessarily the case with the water treatment plant processing water from surface sources. The result of analysis presented here shows that diseconomies of scale exist in the capital cost of a surface water treatment plant in a capacity range of 1-12 million gallon per day (mgd), the widely used, intermediate range. The scale effects on the total cost of water treatment including capital and operating costs are less definite because of lack of operating cost data on the plants included in the above analysis. But there is a strong indication that diseconomies of scale exist for plants larger than 4 or 5 mgd.

The relationship between the capacity and capital cost of a plant is usually given by the following power function proposed by Chenery (1952):

$$C = aK^b \tag{1}$$

where $\underline{C}$ is capital cost, $\underline{K}$ capacity, and $\underline{a}$ and $\underline{b}$ constant parameters. The cost will increase with capacity at a decreasing, constant, or increasing rate depending on whether $\underline{b}$ is less than, equal to, or greater than unity. Thus, Haldi and Whitcomb (1967) called $\underline{b}$ the "scale factor." Most past studies on scale effects reported the existence of economies of scale. For example, Chilton (1960) estimated an average value of $\underline{b}$ to be .68 on plants producing 36 chemical and metal products; Moore (1959) obtained the values of $\underline{b}$ distributed between .8 and 1 on plants producing various aluminum products; and Haldi and Whitcomb (1967) analyzed data on 687

common types of industrial equipment used in chemical and other process industries and obtained b less than unity on 618 (90.0%), b equal to unity on 50 (7.3%), and b greater than unity on 19 (2.8%).

In the water utility field, there were two well-known studies on the relationship between the capacity and capital cost of a surface-water treatment plant. Orlob and Lindorf (1958) estimated the value of b to be .67 on some 15 California plants of unspecified construction dates. Koenig (1967) obtained .68 for b on 21 plants which had undergone last major improvements during the period of 1939-1965. The closeness of the values of b obtained in the two studies might mean that the sets of plants analyzed by these studies had similar age and size distributions. The findings of the present study are quite different from those of the two studies perhaps due to a significant difference in age distribution between the set of plants included in the former and the sets included in the latter.

Demands for Municipal Water

Water treatment plants are owned mostly by municipal or county governments and to some extent by private companies. The capacities of these plants are required by the state to satisfy maximum daily demands of the areas they serve. In most communities, peak daily demands by residential users are the most important factor in determining the capacity of a water supply system. Commercial users do not materially affect peak municipal demands. Water requirements of industrial users vary considerably with types of industry and characteristics of individual users. Some heavy industrial users rely on their own water supply systems and impose little burden on local water supply systems. In a study covering 41 repre-

sentative areas, Linaweaver, et al. (1967) found that maximum daily demands averaged 259 percent of the annual averages, and peak hourly demands averaged 634 percent of the annual averages. Peak demands arise during summer months when a large number of homes sprinkle their lawns In recent years, water-cooled air conditioners have contributed to a substantial increase in peak demands.

In addition to the regular community demands, the American Insurance Association indirectly imposes an additional requirement for the capacity of a water supply system by charging higher fire insurance rates for municipalities with inadequate water supply. The Association has set up schedules of water flow and its duration based on the population of a municipality, and recommends the volume of water specified by these schedules to be available for fire fighting in the high-value district of an average municipality. Further, the Association recommends that storage should be constructed so as to provide the required fire flow during a period of five days with a maximum daily rate of consumption. The maximum rate may be estimated from the maximum total amount used during any 24-hour period in the past three years. However, the Association determines the specific value of fire flow by the structural conditions and congestion of buildings in the district considered.

If literally followed, the Association's recommendations would enhance the capacity required by the peak hourly demands by about 25 percent for a small city of about 90,000 and less for a larger city. However, a wide practice in industry is that the design capacity of a plant is much less than the size recommended by the Association, being usually set to satisfy the normal maximum daily demands estimated for the planning period. The reason is that the plant's design capacity is usually boosted by

booster pumps by as much as 50 percent for a short duration in cases of extraordinary demands.

Of the factors influencing the capital cost of a water treatment plant, most significant is the source of water treated by the plant. Water sources are divided into two groups: one group is composed of surface sources such as rivers, lakes, and dams, and the other group underground sources. Most large plants belong to the former group. In general, surface water is more polluted and requires a higher degree of treatment than does ground water. As a result, the capital cost of a surface water plant generally is substantially greater than that of a ground water plant of the same capacity.

The capital costs of plants are affected in similar manners by such factors as labor and materials in the same region or in dissimilar manners by such factors as the earth and soil conditions of plant site and the type and degree of treatment required of raw water. Further, over a period of time the capital cost of a plant would be affected by changes in water quality specifications set by the state government or in technologies adopted to the construction method or to the design of a plant component. The overall effects of these changes on the capital cost are not only complex but also variable with time. Reducing such effects is considered essential in analyzing the relationship between capacity and capital cost and may be achieved by limiting the age distribution of plants being analyzed to a relatively short period.

Analysis of Data Collected

The original contractual documents on the construction of a plant

submitted to a water supply agency by an engineering firm are the most reliable sources of information on the capital cost of the plant. Data used in the present study were obtained from such documents available at ten of the largest engineering firms in the field located in Chicago, Boston, New York, and the Central Illinois and the Regional Offices in Chicago of the U. S. Housing and Urban Development Agency and Economic Development Agency. These Federal Agencies finance the construction of a water treatment plant and maintain its contractual documents while the plant is under construction.

Not too many water treatment plants of an intermediate or larger size are built in the country each year, mainly because of the longevity of a plant that is as long as 40 years. As a result, the above firms and agencies provided us with cost data on only 18 surface water treatment plants with capacity equal to or exceeding one mgd which were built during the 10-year period of 1963-1972.

Of the 18 plants, six were not new in strict economic sense. In the preliminary plotting of cost data, these plants were found to be clearly outside the main cluster. Reexamination of their contractual documents of each of the plants revealed that a major cost saving was made possible by building the plant on the readily available site of a replaced or existing plant, by using salvaged materials such pipes and motors of the replaced plant, or by sharing some of the components such as an office building or inlet or outlet pipes with existing plants.

Significantly, these quasi-new plants are usually large plants. For example, the 6 quasi-new plants in our survey had capacities of 4 mgd, 8 mgd, 20 mgd, 24 mgd (2 plants), and 200 mgd. According to 1973 statistics published by the state of Illinois EPA (1973), of the total of

193 surface water treatment plants with a capacity equal to or above one mgd, 4 mgd and 8 mgd represented 53 and 72 percentiles, respectively. As a result, the unwitting inclusion of quasi-new plants in analysis of scale effects would produce the value of b smaller than actual is, thus showing economies of scale which may not be warranted. This might be a possible explanation for why Koenig's and Orlof and Lindorf's studies produced the value of b much smaller than that of the present study.

The final sample used in this study was composed of 12 plants with the following size and age distributions: 1.7 mgd (1971), 2.0 mgd (1970). 3.0 mgd (1971) (2 plants), 4.3 mgd (1971), 4.5 mgd (1970), 6.0 mgd (1967) 10 mgd (1965 and 1970), 11 mgd (1965), and 12 mgd (1968 and 1972). The fact that the age distribution of these plants was relatively small would reduce the effects of technological change on plant capital cost. The above plants belong to the intermediate capacity range of 1-12 mgd that covers most plants in small and medium municipalities. For example, the previously discussed statistics of the State of Illinois EPA (1973), the plants belonging to the above range produced over 46% of the water supplied by all surface water treatment plants excluding two Chicago plants of gigantic sizes, 1440 mgd and 1024 mgd.

Detailed raw data in the contractual documents were edited to the five major plant components: (1) building and structure, (2) equipment, (3) piping, valves and gates, (4) utility work including electric, heating and ventilation work, and (5) site preparation, outside work, and landscaping. The data were then individually adjusted to 1972 price levels by indexes available in the Handy-Whitman Index of Water Utility Construction Costs (1973). The edited costs are listed in Table 1 and the total costs derived from these were plotted in Figure 1.

The total and component costs thus obtained are regression analyzed using the following log-linear form derived from Equation (1):

$$\log C = \log a + b \log K \qquad (2)$$

Table 2 lists the results of the analysis. The total plant as well as all components with the exception of site preparation produced F values being statistically significant at a level of 1%. The F value for site preparation was significant at a level between 1% and 5%, reflecting its random variability.

Significantly, the values of scale factor b for the total plant and all components are greater than unity, indicating diseconomies of scale in capital cost. Using a and b in Table 2, the following cost functions of individual components are obtained:

$$\begin{array}{ll} \text{Site Preparation and Outside Work} & c_1 = 36{,}909K^{1.051} \\ \text{Building and Structure} & c_2 = 97{,}650K^{1.229} \\ \text{Piping, Valves and Gates} & c_3 = 33{,}139K^{1.436} \\ \text{Equipment} & c_4 = 69{,}755K^{1.080} \\ \text{Utility Work} & c_5 = 29{,}720K^{1.399} \end{array} \qquad (3)$$

where all costs are in 1972 dollars and K is capacity in mgd. From the individual functions in (3), the total capital cost of a plant, C, is constructed as follows:

$$C = c_1 + c_2 + c_3 + c_4 + c_5 \qquad (4)$$

For illustration, the total plant cost is plotted and its regression line drawn in Figure 1. The reader is reminded that the function given by this regression line, or $C_a = \$326{,}679K^{1.166}$, is not the same as the

total cost function in (4) because of the use of logarismic values in regression analysis.

Scale Effects on the Unit Total Cost

Whether economies of scale exist in water treatment or not depends on the total unit cost covering capital investment and plant operation. To answer this question, first, the following daily capital cost C_1 is obtained by adjusting the capital cost in (4) with .08883/365, where .08883 represents the amortization factor for a period of 30 years at a rate of 8%:

$$C_1 = \frac{.08883}{365} C \qquad (5)$$

In the previously discussed study, Koenig presented what may be considered the only detailed data published to date on the operating cost of a water treatment plant. Using Koenig's data, Hinomoto (1972) obtained a cost function in terms of 1964 prices for each of the six major factors of operation: chemicals, pumping energy, heating energy, manpower, maintenance and repair, and others. These functions need be adjusted to 1972 prices to be compatible with the capital cost function in (5). The function for chemicals are adjusted by wholesale prices given by the Bureau of Labor Statistics (1964 and 1972) on Aluminum Sulfate, the chemical substance used in the largest quantity in water treatment, the functions for pumping and heating energies by Federal Power Commission's Index of Energy Bill (1973), and the functions for manpower, maintenance and repair, and others by average hourly earnings of water, steam, and sanitary systems workers published by Bureau of Labor Statistics (1973). The total daily costs of major components of operation thus

obtained for a plant with capacity K mgd in capacity operation for 24 hours:

$$
\begin{array}{lll}
\text{Chemicals} & c_6 = 17.12K^{0.675} & \\
\text{Pumping Energy} & c_7 = 33.64K^{0.718} & \\
\text{Heating Energy} & c_8 = 3.71K^{0.481} & \\
\text{Manpower} & c_9 = 44.50K^{0.687} & (6) \\
\text{Maintenance and Repair} & c_{10} = 6.60K^{0.579} & \\
\text{Others} & c_{11} = 1.66K^{0.930} &
\end{array}
$$

where each cost is in 1972 dollars. Thus, the total daily cost of operation for a plant with capacity K mgd is given by the following C_2:

$$C_2 = c_6 + c_7 + c_8 + c_9 + c_{10} + c_{11} \tag{7}$$

Water treatment requirements and basic treatment techniques have practically unchanged since the time of Koenig's study. Thus all functions in (6) are still considered valid for recently built plants, except that larger recent plants might use more labor saving devices than comparable plants in Koenig's study. Taking the possible technological change into consideration, the total and unit costs of water treatment have been computed under two different conditions. One condition assumes that all functions in (6) are valid for the plants in our study, whereas the other condition assumes the validity of all functions except for the manpower cost function. This function is replaced by a condition representing an extreme case of labor saving in which all plants use the same amount of labor as required by a plant with the smallest capacity, 1 mgd, in the capacity range under consideration. The actual labor savings realized by the plants in our study are expected to be somewhere between

the above two conditions.

The unit total costs computed under the two conditions are listed in the right-most columns of Table 3. In both cases, the total unit cost first decreases, reaches a minimum, and then continuously increases with capacity. The minimum total unit cost is reached at 4 mgd under the first condition but at 5 mgd under the second condition thus indicating that the actual optimum capacity perhaps is somewhere between 4 and 5 mgd. This means that a major part of municipal water in this country is supplied by plants whose capacities are in the region of diseconomies of scale. In Illinois, 76% of municipal water from surface sources, except for water supplied by the two enormous plants in Chicago, was supplied by plants considered in the region of diseconomies of scale.

Conclusion

This study determined the scale factor of the capital cost of a surface water treatment plant from cost data obtained from the contractual documents originally submitted by engineering firms to water supply agencies. The result indicated diseconomies of scale existing in each of the major components of a plant with a capacity in the range of 1-12 mgd.

To determine the existence of similar diseconomies in the total cost of water treatment including capital and operating costs, the cost functions for major elements of plant operation derived from Koenig's study were used under two different conditions. The first condition assumed the validity of all the cost functions for our plants, while the second condition assumed the validity of all of them except the manpower cost function. Assuming an extreme case of automation, the labor cost under the second condition was fixed for all plants at the amount required by

a plant with a capacity of 1 mgd. Under both conditions, the unit total cost decreased at the beginning, reached a minimum at a capacity of 4 or 5 mgd, and then continuously increased with an increase in capacity. Thus we concluded many plants in water utility were constructed with capacities in the range of diseconomies of scale.

As one of the findings in examination of the original contractual documents, some of the officially new water treatment plants were found to be not strictly new in economic sense. They were built at readily available sites left by the replaced plants or adjoining to the existing plants, thus realizing cost savings in site preparation. Sometimes their cost savings were realized by using materials salvaged from the replaced plants or sharing equipment with the existing plants. Since such plants tend to be large in capacity, unwitting inclusion of their data in the analysis would produce a value of scale factor smaller than the actual value.

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Table 1. Total and Component Costs of Surface Water Treatment Plants

(in 1972 price levels)

Plant no.	Construction year	Capacity (mgd)	Component Cost of Plant Construction					Total Cost of Plant Construction
			Site Preparation	Building and Structure	Piping, Valves and Gates	Equipment	Electric, Heating, and Ventilation	
1	1971	1.7	$ 21,574	$ 272,922	$ 71,337	$ 127,713	$ 57,663	$ 551,209
2	1970	2.0	32,753	414,097	93,927	238,577	75,962	855,316
3	1971	3.0	154,527	549,695	197,518	258,862	181,656	1,342,258
4	1971	3.0	762,469	109,888	123,404	360,860	205,359	1,561,980
5	1971	4.3	522,860	456,092	353,102	280,889	330,529	1,943,472
6	1970	4.5	107,867	389,982	254,611	188,133	100,816	1,041,409
7	1967	6.0	321,480	870,203	263,210	183,666	250,479	1,889,038
8	1965	10.0	463,815	2,234,079	1,055,067	636,912	769,783	5,159,656
9	1970	10.0	177,215	2,498,319	1,729,804	1,006,328	850,753	6,262,419
10	1965	11.0	333,699	1,450,864	1,412,195	1,140,447	913,738	5,250,943
11	1972	12.0	544,435	2,292,500	886,686	1,458,000	916,019	6,097,640
12	1968	12.0	449,159	2,163,892	732,839	1,530,222	1,118,395	5,994,507

Table 2. Parameters of Capital Cost Functions for Surface Water Treatment Plant and Its Components (in 1972 price levels)

Cost Component	Intercept a	Scale Factor b	F Ratio
Site Preparation	$36,909	1.051	7.86
Building and Structure	97,650	1.229	30.84
Piping, Valves, and Gates	33,139	1.436	89.97
Equipment	69,755	1.080	30.91
Electric, Heating, and Ventilation Work	29,720	1.399	82.36
Plant Total	326,679	1.166	112.59

Table 3. Unit Total Costs of Water Treatment

by Plants of Various Capacities

(in 1972 price levels)

Capacity (mgd)	Daily Capital Cost ($)	Daily Operating Cost($)		Daily Total Cost($)		Unit Total Cost($/mg)	
		Condition 1*	Condition 2**	Condition 1	Condition 2	Condition 1	Condition 2
1	65.0	107.2	107.2	172.2	172.2	172.2	172.2
2	151.1	172.5	145.3	323.6	296.4	161.8	148.2
3	248.4	227.9	177.8	476.4	426.3	158.8	142.1
4	354.3	277.9	207.1	632.3	561.4	158.0	140.3
5	467.1	324.2	234.2	791.3	701.4	158.2	140.2
6	585.9	367.7	259.8	953.6	845.7	158.9	140.9
7	709.9	409.0	284.1	1119.0	994.1	159.8	142.0
8	838.7	448.6	307.0	1287.4	1146.2	160.9	143.2
9	971.9	486.7	329.9	1458.6	1301.8	162.0	144.6
10	1109.1	523.5	351.6	1632.7	1460.7	163.2	146.0
11	1250.0	559.3	372.7	1809.3	1622.7	164.4	147.5
12	1394.5	594.0	393.2	1988.6	1787.6	165.7	148.9

Note: * Condition 1 assumes manpower requirements variable with capacity as given by c_q in (6).

** Condition 2 assumes that the manpower requirements for a 1-mgd plant apply to plants of all sizes.

Figure 1. Total Construction Costs of Plants in the Sample